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LCA Methodology

Regional Scaling and Normalization in LCIA

Development and Application of Methods

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Abstract

Methodologies for regional scaling and normalization steps in life-cycle impact assessment (LCIA) were developed and applied to two case studies in connection with the equivalency factor type of hazard characterization approach. Regional scaling factors are numerical scores used to indicate ranges of the degree of sensitivity that a particular region has for the selected impact category. These factors were developed to modify and improve the accuracy of partial equivalency factors for five impact categories. Normalization is the process of defining the relative contribution of the characterization scores by impact category to the total impact for the same category. Normalization factors were developed that represent the total, annual, geographically relevant, impact potential (hazard potential from emission loading or resource use) for a given impact category. Global or U.S. data were obtained to develop normalization factors representing 14 impact categories considered to be relevant to three spatial areas: global, state, and facility. The regional scaling and normalization methods improved the ability to evaluate two LCIA case studies in the U.S. and increased the accuracy of conclusions about which alternative processes or individual impact categories had the greatest potential hazard for environmental effects.

Keywords: Environmental effects, LCA; equivalency factor; hazard characterization; hazard potential; impact categories; LCIA; Life Cycle Impact Assessment (LCIA); normalization in LCIA; regional scaling; spatial perspectives

1 Introduction to Regional Scaling and Normalization

The basic conceptual framework for a life-cycle impact assessment (LCIA) was originally defined by the Society of Environmental Toxicology and Chemistry (SETAC, 1993a) to include three steps in addition to scoping: classification, characterization, and valuation. These steps have been described in more detail in the SETAC (1993b) "Code of Practice" guidelines for Life Cycle Assessment (LCA) and in an LCIA framework document by the U.S. Environmental Protection Agency (EPA, 1995a). However, it is important to note that these LCIA steps are still in an early stage of methodological development that is in the process of being tested. More recently, the need to include regional scaling (OWENS, 1996; HOGAN et al., 1996; UDO DE HAES, 1996) and normalization (GUINÉE, 1995) as part of the characterization step have been identified. This paper focuses on the development and refinement of these two methods for improving the accuracy of the impact characterization step and applies them as part of equivalency models to two LCIA case studies. The equivalency models used in this paper are assessments of potential hazard and not a representation of actual impacts.

1.1 Definitions

Regional scaling factors are needed for impact criteria (e.g., acid deposition or water use) whose potential impacts have either a regional or local spatial environmental sensitivity. For these impact categories, environmental conditions (e.g., soil neutralization capacity or rainfall) in different locations cause the same emission or resource use quantity to have a different magnitude of potential impact in different locations. For example, some locations/regions (e.g., Los Angeles, California) may be highly sensitive to one of these impacts (e.g., smog) and other locations may be only moderately sensitive or may not be sensitive to any potential impact at all from the same quantity of emissions. Regional scaling factors are numerical scores used to indicate ranges of the degree of sensitivity that a particular region has for the selected impact category. Regional scaling is a way of improving the accuracy of the "track 1" method described in a document from SETAC Europe (UDO DE HAES, 1996), which deals with the assessment of potential impacts of non-localized systems. However, regional scaling still does not have the accuracy of the "track 2" method, which deals with localized unit operations using environmental impact assessment or risk assessment.

Normalization is one way of analyzing or gaining perspective on characterization results prior to valuation of LCIA data, because aggregated characterization sums per impact category need to be expressed from a similar perspective before assigning valuation weight factors. Normalization factors have been described as the current existing upper limit of potential impacts within an impact category for a selected geographic area (SETAC, 1993b). Normalization has also been described as the process of defining the relative contribution of the characterization scores by impact category to the total environmental burden for that category (GUINÉE, 1995). This can be accomplished by dividing the characterization score for an impact category by the total extent of the relevant potential impact score for a certain area and a certain period of time. The initial approach to normalization factors by some practitioners has involved values for the entire world, particularly where most of the impact categories considered are global in nature (e.g., GUINÉE, 1995). OWENS (1995) has submitted recommendations of the U.S. delegation to the International Organization for Standards (Technical Committee 207, Subcommittee 5, working group 4) that LCIA should include a normalization step to understand the relative contribution that the sum from impact characterization of inventory data for an impact category makes relative to the actual environmental effects for that impact category. Normalization should be used to interpret characterization results by considering the actual occurrence, including magnitude and frequency, of the effects in each impact category, as well as the relation of the LCA system contribution to the overall anthropogenic and natural contributions.

1.2 Absence in most LCIAs

Despite the potential for regional scaling and normalization to improve the accuracy of impact characterization, these methods have rarely been used in published LCIAs. GUINÉE (1995) has suggested global normalization values for ten impact categories as part of a methodological case study of margarine, even though several of the impact categories listed (e.g., acidification and human toxicity) are clearly regional or local in spatial scale. HOGAN et al. (1996) have proposed an approach similar to regional scaling, but the method was restricted to criteria air pollutants and their impact on human health. The regional scaling method described by HOGAN et al. (1996) involved an initial screening using the "less-is-best" approach on inventory data prior to application of regional scaling. Thus, some chemicals with a high impact potential in an impact subcategory, but whose quantity did not differ by more than 25% between alternatives, could be eliminated from further consideration during the initial screening before impact characterization is conducted.

As pointed out by OWENS (1996), most LCIAs do not consider actual environmental relevance. For some systems, "incomplete LCI data, emission complexity and diversity, and site-specific conditions preclude LCI/LCIA use to assess real or even potential effects", particularly for non-global impact categories. The regional scaling and geographically relevant normalization approaches discussed here can bring the potential for actual effects into clearer focus.

1.3 Focus on U.S. application

The approach for regional scaling and normalization described here is potentially applicable internationally, but the specific databases and documents used to implement the regional and local aspects of this approach and the two case studies used to test the method are restricted to the U.S. For example, the primary, U.S., chemical emission databases required to implement this method are the Toxic Release Inventory (TRI) and the Aerometric Information and Retrieval System (AIRS EXEC). Caution should be observed in evaluating TRI data, since these numbers are estimated rather than measured emissions. Similar databases and environmental sensitivity maps specific to other countries need to be identified to make this method equally useful in other countries. One example is a map of the critical loads of acidity for soils in Great Britain (HORNUNG et al., 1995), which could be used to develop regional scaling factors for Acid Deposition. Another example is the critical load maps for nitrogen deposition in Sweden (GUNDERSEN, 1992), which could be used to develop regional scaling factors for terrestrial Eutrophication potential. Similarly, maps of critical loads of nitrogen and sulfur deposition for lakes in Finland, Norway, and Sweden are provided by POSCH et al. (1997). Other suitable maps for regional scaling in Europe are referenced in a SETAC-Europe Workshop Report on LCIA methodology (UDO DE HAES, 1996).

2 Case Studies Used to Test Methods

The two case studies used for testing the methods were streamlined LCIAs on conventional and alternative processes for 1,4-butanediol (BDO) production (EPA, 1997a) and a baseline evaluation for production of the GBU-24 bomb (1997b). The BDO case study focused on comparative LCIAs of the conventional feedstock process based primarily on natural gas and an alternative feedstock process based on corn-derived glucose. The conventional feedstock process included natural gas production and processing, acetylene and formaldehyde production, and production of BDO by the Reppe process. The Reppe process reacts acetylene and formaldehyde to produce 1,4-butenediol, which is subsequently hydrogenated to BDO. The alternative feedstock process involved corn production, wet corn milling, fermentation of glucose to succinic acid, and catalytic reduction of succinic acid to BDO. This study was conducted for the U.S. Department of Energy's (DOE's) Alternative Feedstocks Program and EPA's National Risk Management Research Laboratory (NRMRL), Sustainable

Technology Division. Both the EPA portion of the BDO study and the GBU-24 study were funded by the Strategic Environmental Research and Development Program.

For the GBU-24 case study, the U.S. Department of Defense, DOE, and EPA/NRMRL cooperated in a program to develop technologies for the clean production of propellants, energetics, and pyrotechnic materials. The primary goal of the GBU-24 case study was to demonstrate the use of the LCIA methodology using inventory data collected under the Strategic Environmental Research and Development Program. The GBU-24 life cycle included:

1. extraction and production of raw materials
2. synthesis of RDX explosive and formulation and blending into CXM-7 explosive at Holston Army Ammunition Plant in Kingston, Tennessee
3. load/assemble/pack PBXN-109 (CXM-7, aluminum powder, thermoset plastic binder, and blending and forming agents) into steel bomb body at McAlester Army Ammunition Plant in McAlester, Oklahoma
4. demilitarization and materials recovery at the Naval Surface Warfare Center in Indian Head, Maryland. Significant energy consumption occurs at Holston (coal-based) and McAlester (natural gas-based).

3 Impact Category Classification and Equivalency Characterization

Classification was conducted after scoping and is the process of linking or assigning data from the LCI to individual stressor categories within the three major stressor categories of human health, ecological health, and resource depletion. Stressor/impact networks were prepared for interpretation of the inventory information and to facilitate selection of the 14 primary impact categories (→ *Table 1*) planned for impact analysis in at least one of the two test cases.

Table 1: Major stressor categories, equivalency type, spatial scale, and use of regional scaling factors for 14 impact categories evaluated in one or both case studies

Categories of Potential Impact	Major Stressor Categories			Equiva-Lency Type	Area Selected For Normal-ization	Regional Sensitivity Scaling Factor
	Human Health	Ecolog-ical Health	Resource Depletion/ Land Use			
Ozone Depletion	X	X		Full	Global	
Global Warming	X	X		Full	Global	
Resource Depletion			X	Partial	Global	
Acid Deposition	X	X		Partial	State[a]	Yes
Smog Creation	X	X		Partial	State	Yes
Water Use			X	None	State	Yes
Suspended (PM_{10}) Particulates	X	X		None	State	Yes
Human Inhalation Toxicity	X			Partial	Facility[b]	
Carcinogenicity	X	X		Partial	State	
Solid Waste Disposal Land Use			X	Partial	State	
Resource Extract./Prod. Land Use			X	None	State	
Terrestrial (Wildlife) Toxicity		X		Partial	Facility[b]	
Aquatic (Fish) Toxicity		X		Partial	Facility[b]	
Eutrophication		X		Partial	State	Yes

[a]Normalized by maximum U.S. state emission or resource use
[b]Normalized by maximum emission from U.S. facility

Quantitative or semi-quantitative equivalency factors were adopted or developed for 11 of the 14 impact categories in accordance with the SETAC (1993a) Level 2 or 3 characterization approaches. The remaining three of the 14 impact categories did not need equivalency factors to aggregate stressors, because there was only one stressor in the category. The equivalency factors used included two full and nine partial equivalencies (→ *Table 1*) as defined below.

3.1 Full equivalencies

Full equivalencies are those quantitative factors with international scientific support that include a number of properties, such as potency, environmental half-life, and global effects. Full equivalency factors were adopted without modification from HEIJUNGS (1992) for two global-scale impact categories (→ *Table 1*), because there is international support for the factors used. Global warming and ozone depletion equivalency factors are supported, respectively, by the International Panel on Climate Change (IPCC, 1992) and the World Meteorological Organization.

3.2 Partial equivalencies

Partial (approximate) equivalency factors are those semi-quantitative factors where part of the formula is quantitative, but some approximation and assumptions are required to account for differences in regional or local sensitivity to environmental conditions or background loading of stressors from other sources. Partial equivalency factors were developed for nine of the 12 remaining impact categories (→ *Table 1*). Regional scaling factors were incorporated into the partial equivalencies for three of the categories (Acid Deposition, Smog Creation, and Eutrophication), because previously available equivalency factors reported in HEIJUNGS (1992) do not account for differences in regional sensitivity resulting from different environmental conditions (e.g., pH buffering capacity). Background loading from sources in the same area (surrogate for background concentration or deposition loading) that are not part of the LCI under study were included in determining regional sensitivity, since the impact potential is much greater in environmentally sensitive areas that also have high background concentrations from other sources. Air deposition modeling is underway to develop maps of average background air concentrations or deposition quantities by state contributing to these impact categories, which will replace the maps of emission sources.

The equivalency factors for the Solid Waste Disposal impact criterion under Land Use are based on the estimated volume calculated using the specific weight (in kg/m^3) of each type of solid waste. Since the LCI data for solid wastes are expressed as weight/functional unit, multiplication of the weight and inverse of the specific weight describes the landfill volume required.

The basis for Resource Depletion equivalency factors was the inverse of the resource depletion time for a given year, which can be expressed as the world annual production of a mineral or fossil fuel divided by the world reserve base. This is similar to the "reserve-to-use" ratio described by LINDFORS (1995), except that production is used as a surrogate for consumption and reserve base is used instead of reserves. The Minerals Commodity Summary information dated January 1996, which contains data for 1995, was obtained from the U.S. Geological Survey's, Minerals Information Center (previously the U.S. Bureau of Mines) on the World Wide Web. The fossil fuel data were based on global reserves and production, and were obtained from the Annual Energy Review for 1994 by DOE's Energy Information Administration (DOE/EIA, 1995). The Resource Depletion equivalency factors do not take into account potential technological advancements for economically locating or mining natural resource deposits not currently included in the reserve base. Also, the scores do not consider the influence of increased recycling on decreasing the demand for remaining reserves.

The approach for calculating equivalency factors for the three toxicity and one Carcinogenicity impact criteria was modified from an EPA (1994) chemical hazard evaluation document prepared by the University of Tennessee and summarized by SWANSON et al. (1997). The equivalency factors for Human Health Inhalation Toxicity, Terrestrial Toxicity, and Aquatic Toxicity were determined by multiplying the hazard value for toxicity times the sum of the hazard values for persistence and bioaccumulation, as discussed in a conceptual framework document by SETAC (1993a) for a Level 3 approach. Acute toxicity values were used to develop the equivalency factors, because chronic toxicity values (including estimated QSAR values) are unavailable for many chemicals, particularly for terrestrial species. Acute toxicity values for the most sensitive species (lowest LD_{50} or LC_{50}) were used for the following animal groups and test types to develop equivalency factors for each of the three toxicity impact categories: human health inhalation toxicity (rodent, 4-hr, inhalation LC_{50}), terrestrial toxicity (rodent, oral LD_{50}), and aquatic toxicity (fish, 96-hr, LC_{50}). Although chronic toxicity values would be preferable, if more were available, it is better to use acute toxicity values for combining chemicals within an impact category, than to omit many toxic chemicals from the calculations because no chronic toxicity data exist. Equivalency factors for toxic chemicals released to soil and water emphasized toxicity data for wildlife and fish, respectively, and not humans, because the diet for wild species is typically restricted to a small area and water supplies are untreated. On the other hand, areas with heavily polluted soil and water are typically restricted from human access and drinking water for humans is usually monitored and treated in municipal systems. Also, toxicity data from animal tests are usually used to set safe food and drinking water chemical concentration levels for humans.

The Carcinogenicity equivalency factors were determined by a weight-of-evidence (WOE) approach, which scored carcinogen classification information by EPA and the Inter-

national Agency for Research on Cancer (IARC) according to the nature of the animal and epidemiological research evidence. Although the cancer potency factors developed by EPA and reported in the IRIS database could have been used to develop the carcinogen equivalency factor, many carcinogens did not have a cancer potency factor calculated at the time of the study.

4 Regional Scaling Methods

Regional scaling factors were developed for the following five impact criteria: Suspended Particulate (PM_{10}) Effects, Water Use, Acid Deposition, Smog Creation, and Eutrophication. For each one of these five impact categories, different levels of sensitivity throughout the U.S. were defined and linked with scaling factors for use in refining the final impact category scores. In each case, the scaling factors (numbers 9,7,5,3 or 1) were applied to ranges of sensitivity, where 9 is the most sensitive to a particular impact category and 1 is the least sensitive. In most cases, these scaling factors were determined by compositing information indicated on maps that contribute to sensitivity for a particular impact category, such as water use and availability, sensitive receptor distribution, emission sources, and/or emission deposition quantities. For each of the five impact criteria, the scaling factors for different areas in a state were averaged over the entire state for a particular impact category according to the percent of surface area covered within a particular state. These average state scaling factors were necessary to permit allocating inventory emissions among states, when specific facility locations were not known or too numerous (e.g., emissions associated with the national grid of electric power generation plants). Thus, the average state scaling factors were multiplied by the corresponding state inventory data after allocating inventory data to individual states. A concern associated with using an average scaling factor for the entire state is that large states (e.g., California or Texas) may have wide variation in sensitivity to a particular impact category. However, some inventory data are very difficult to obtain for portions of a state, so land area resolution of the scaling factor would not be helpful. Furthermore, the utility of regional scaling factors, as described in the first section, is to improve the assessment of potential hazard overall ("track 1"), not to evaluate site-specific impacts ("track 2").

This approach for regional scaling emphasizes two of the four "dimensions of impact information" listed by UDO DE HAES (1996) for improving the sophistication of characterization. Background level information is represented, because the magnitude of a chemical's potential impact to an ecosystem is dependent on the existing background concentration. Maps of emission sources, emission deposition quantities, and criteria pollutant non-attainment areas were used as indicators of background concentrations. Although air emissions can be carried 100s of km from the source, especially with tall stacks, an assumption was made that the majority of air emissions would be deposited or cause an effect in the same state they were released (e.g., suspended particulates or VOCs). This assumption is only reasonable where the LCA includes many emission sources and would be inappropriate for site-specific analyses. Although not available at the time of this research, air deposition modeling has recently been conducted for acid precursors to replace the use of emission source information in developing Acid Deposition regional scaling factors.

Spatial information was another dimension used to improve the accuracy of characterization. As suggested by UDO DE HAES (1996), regional problems like acidification can benefit by the use of maps representing regions with different sensitivity levels. Thus, maps of acid sensitive soils or lakes were used to develop regional scaling factors.

4.1 Suspended (PM_{10}) particulates

LCI data on total suspended particulates (TSP) were converted to particulate matter less than 10μ (PM_{10}), since this is the size considered to pose the greatest human health hazard from inhalation. These emission quantities were allocated to each state and multiplied by the state scaling factor. The information used to develop the scaling factor for each state is as follows:

1. U.S. map of facilities emitting ≥90.7 metric tons per year (MTPY) (equals 100 tons per year) PM_{10} (EPA, 1995b)
2. U.S. map of PM_{10} non-attainment areas (EPA, 1995b)
3. approximate MTPY of PM_{10} from facilities included in LCI.

Emission sources in the LCI were ranked as large (>90.7 MTPY), medium (90.7-13.6 MTPY), or small (<13.6 MTPY), and the scaling factor was increased with increasing size of the facility. These same size categories are used in the National Ambient Air Quality Standard (NAAQS) regulations for the U.S. Although the map of large stationary sources excludes a significant contribution to particulate loading from vehicles, these were combined with PM_{10} non-attainment areas, which do include the particulate contribution from mobile sources. The unweighted, factored value for PM_{10} for one state was determined by multiplying the regional scaling factor for a given state times the percent of PM_{10} emissions allocated to that state. The total unweighted, factored PM_{10} score for the U.S. was determined by adding the regionally-scaled PM_{10} values for all states combined.

4.2 Water use

Scaling factors developed for Water Use in each state are based on availability indicated in two U.S. maps showing areas of inadequate surface water supply for instream use (flowing rivers and streams) and groundwater overdraft (VAN DER LEEDEN et al., 1990), as well as use rates indicated in a map showing freshwater consumptive use by state (SOLLEY et al., 1993). First, the inadequacy of surface water

supply for instream use (i.e., stream flow reduced by off-stream uses or drought) is determined from a map in VAN DER LEEDEN et al. (1990) for the area being evaluated and a numeric value from 1 to 3 is assigned (i.e., 1 is assigned for 70% or more depleted in an average year, 2 if 70% or more is depleted in a dry year, and 3 if less than 70% is depleted). Second, the groundwater overdraft (including irrigation) situation for the area is determined from a map in VAN DER LEEDEN et al. (1990) and a numeric value of either 1 or 3 is assigned. The value 1 is assigned if the overdraft situation is critical (i.e., more than 1.89 billion liters per day (BLD), which equals 500 million gallons per day); a 3 is assigned if the groundwater overdraft situation is moderate (0.79 to 1.89 BLD) or nonexistent. Because groundwater overdraft has less impact on factors such as stream biota and habitat, only two levels are differentiated so that more emphasis is placed on the critical overdraft situation and the instream availability. Regional scaling of water use is suggested in both LINDFORS et al. (1995) and UDO DE HAES (1996), but a detailed methodology was not included.

Once the two numeric availability values for instream surface water use and ground water overdraft were determined, they were added together to give a ranking that ranged from 2 to 6. In this case, 2 is the worst possible value (a 1 for surface water indicating >70% depletion for average year, and a 1 for groundwater overdraft indicating a critical situation with an overdraft of >1.89 BLD). The sum of the water availability scores was then converted to (→) a preliminary equivalency factor so that the highest equivalency factor was associated with the lowest water availability sum, according to the following conversions: 2→9, 3→7, 4→5, 5→3, and 6→1.

The third factor, consumptive water use, refers to that part of the water withdrawn that is evaporated, transpired, incorporated into products and corps, consumed by humans or livestock, or otherwise removed from the immediate water supply. If consumptive water use was in one of the two highest categories shown in the map by SOLLEY et al. (1993) (i.e. either 45.42 to 79.49 BLD or 15.14 to 45.42 BLD and the availability score was a 3,5, or 7) the initial score was subjectively increased to the next highest category (e.g., 3 becomes a 5).

For example, based on the maps cited above, the state of Colorado had a surface water supply score of 2 and a ground water overdraft score of 3, for a water supply sum of 5. The water supply sum converts to a preliminary equivalency factor of 3. The preliminary equivalency factor is raised to a final value of 5, because the consumptive water use is in one of the two highest consumptive water use categories.

4.3 Acid deposition

Regional scaling factors for Acid Deposition potential (→ *Fig. 1*) were developed by making a composite map of the U.S., which combined maps of areas of acid-sensitive soil and surface water, with maps of large emission sources. The primary considerations in making the composite map were maps of regions with acid sensitive lakes, based on bedrock geology (DOE, 1981) and regions with soils sensitive to acid deposition in the Eastern U.S. (MCFEE, 1980). A minor modifying influence in developing the composite map was U.S. maps of facilities emitting ≥90.7 MTPY of SO_x or NO_2 (EPA, 1995b). Scaling factors for Acid Deposition potential in each state (→ *Fig. 1*) were obtained by using the average state value from the composite map, based on the area covered by each value in that state. This value represents the average within the state, but not every point within the state will have this level of sensitivity. The unweighted, factored value for a given chemical (e.g., SO_x) for one state was determined by multiplying the regional scaling factor for a given state, times the percent of emissions for the particular chemical allocated to that state, and times the equivalency factor for the particular chemical. The total unweighted, factored score for a particular chemical contributing to Acid Deposition throughout the U.S. was determined by adding the regionally scaled and factored values for that particular chemical for all states combined.

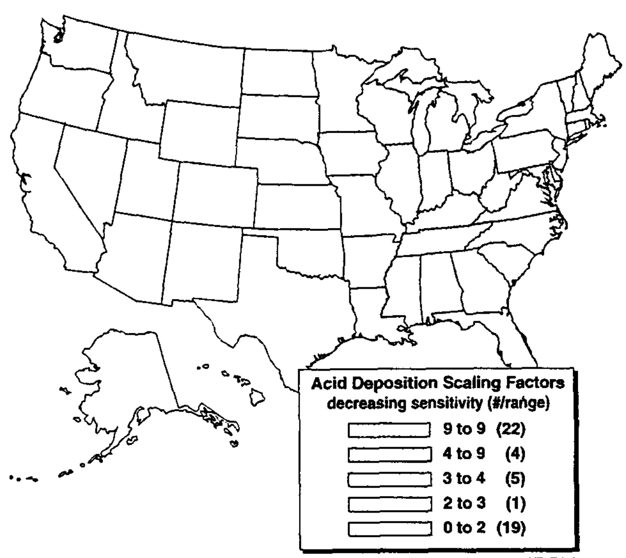

Fig. 1: Regional scaling factors for acid deposition by state

Development of Acid Deposition regional scaling factors by using an air transport model to determine areas where acid precursors emitted from the system under evaluation are likely to be deposited would be more accurate in predicting potential impacts than the information on the states where they are emitted. However, given that all of the states in the northeastern U.S. were assigned the highest regional scaling factor (→ *Fig. 1*), and given that the amount of acid precursors exported from a state often equals the amount imported from other states, the end result of the air transport modeling would be unlikely to change the overall score for an LCA involving numerous emission sources in the U.S.

4.4 Smog creation

Regional scaling factors for photochemical oxidant ("Smog") Creation potential were developed by making a composite map of the U.S., which combines information on major emission sources and background concentrations from the following maps:

1. two U.S. maps of facilities emitting ≥90.7 MTPY of VOCs and NO_2 (EPA, 1995b)
2. two U.S. maps of Ozone and NO_2 non-attainment areas (EPA, 1995b).

Although the map of large stationary sources excludes a significant contribution from small stationary and mobile sources, they were combined with the maps of ozone and NO_2 non-attainment areas, which do include the contribution from these smaller sources. Scaling factors for Smog Creation potential in each state were obtained by using the average state value from the composite map, based on the area covered by each value in that state. Calculation of the unweighted, factored score for Smog Creation potential was done in the same fashion as for Acid Deposition, except that the chemicals included were only those contributing to smog.

4.5 Eutrophication

Regional scaling factors for Eutrophication potential were developed by making a composite map of the U.S., which combines information on nutrient deposition and watershed input quantities from the following three types of color maps found in PUCKETT (1995):

1. U.S. map of atmospheric deposition of nitrogen
2. U.S. maps of nitrogen and phosphorus input to watersheds from animal manure
3. U.S. maps of nitrogen and phosphorus input to watersheds from fertilizer.

Scaling factors for Eutrophication potential in each state were obtained by using the average state value from the composite map, based on the area covered by each value in that state. Calculation of the unweighted, factored score for Eutrophication potential was done in the same fashion as for Acid Deposition, except that the chemicals included were only those contributing to Eutrophication.

Non-point sources of nutrient loading were emphasized, because in the U.S., non-point sources of nitrogen and phosphorus dwarf point sources (including sewage treatment plants) of these nutrients (PUCKETT, 1995). Even in urban areas, where point source nutrient inputs are highest, they were still less than nutrient inputs from manure and the atmosphere. For example, in the highly populated northeastern U.S. nitrogen loading to watersheds from point sources is only 10% and 30%, respectively, of the nitrogen loading from the atmosphere and manure. It should be noted that the areas on the maps with increased nutrient loading do not indicate the degree of existing eutrophication. These areas of high nutrient loads have the potential for eutrophication in some water bodies within the state, if they are further increased by nutrient emissions associated with the LCA. Eutrophication is more likely in water bodies with either a nutrient poor environment or where the assimilation capacity has been, or has almost been, exceeded (UDO DE HAES, 1996).

The impact of concern for the Eutrophication potential impact category is nutrient overload in surface waters from either direct input into a water body or from overland runoff following terrestrial deposition of nutrients. The nutrient overload triggers an algal bloom and dieoff, resulting in death of aquatic biota due to oxygen depletion associated with algal decay. This description of impact potential matches the aquatic impacts discussed in LINDFORS et al. (1995).

4.6 Matrix of regional scaling factors by state

The geographic scaling factors for each of the five impact criteria discussed above are shown by state in **Table 2** (→ *see p. 204*), where the larger numbers indicate the greater sensitivity to the impact category. Separate scaling factors were used for Suspended Particulates (PM_{10}), depending on whether the source used for the LCI was considered medium (13.6-90.7 MTPY) or large (≥90.7 MTPY).

5 Normalization Methods

In this study, the normalization approach involves the determination of factors that represent the total, annual, geographically relevant impact potential for a given impact category. The goal is to develop scientifically defensible normalization factors, making use of existing emissions or resource extraction data. Impact categories are divided according to three spatial areas: global, state, or facility (→ *Table 1*).

5.1 Global-normalized impact categories

Global-normalized impact categories include Ozone Depletion, Global Warming, and Resource Depletion, because the total impact potential in these categories is assumed to be independent of the geographic location in which emissions are released or resources are extracted. The normalization factor for Resource Depletion was calculated as the global production of a given resource times the equivalency factor (global production divided by global reserves) for that same resource. The equivalency factor is the global use rate specific to each resource type. As with the other impact categories, the impact quantities were computed to get the total global impact of resource use, which was used as the normalization factor.

Table 2: Regional scaling factors for five impact criteria by state

STATE[b]	ACID DEPOSITION	EUTROPHI-CATION	SMOG	PM-10 MEDIUM SOURCE	PM-10 LARGE SOURCE	WATER USE
AL	3	5	7	3	5	1
AK	NA[c]	NA	NA	3	5	1
AZ	1	1	3	7	9	9
AR	1	5	7	3	5	3
CA	2	5	9	7	9	9
CO	1	3	3	7	9	5
CT	9	7	9	3	5	1
DE	9	7	9	3	5	1
DC	9	7	9	3	5	1
FL	4	5	7	3	5	1
GA	5	5	7	3	5	1
HI	NA	NA	NA	3	5	1
ID	3	1	1	7	9	3
IL	9	7	7	7	9	1
IN	9	7	7	7	9	1
IA	1	7	5	3	5	1
KS	1	5	3	3	5	5
KY	9	7	8	3	5	1
LA	1	5	8	3	5	1
ME	9	3	8	7	9	1
MD	9	7	9	3	5	1
MA	9	7	9	3	5	1
MI	9	6	6	7	9	1
MN	5	5	3	7	9	1
MS	3	5	7	3	5	1
MO	1	7	6	3	5	1
MT	1	1	1	7	9	1
NE	1	5	3	3	5	9
NV	1	1	1	7	9	5
NH	9	7	8	3	5	1
NJ	9	7	9	3	5	1
NM	1	1	3	7	9	7
NY	9	8	8	3	5	1
NC	9	5	7	3	5	1
ND	1	2	2	3	5	1
OH	9	8	8	7	9	1
OK	1	5	5	3	5	7
OR	3	1	5	7	9	1
PA	9	9	8	7	9	1
RI	9	7	9	3	5	1
SC	5	5	7	3	5	1
SD	1	4	3	3	5	1
TN	9	6	7	3	5	1
TX	1	3	8	7	9	9
UT	1	1	1	7	9	7
VT	9	7	8	3	5	1
VA	9	7	7	3	5	1
WA	3	5	7	7	9	1
WV	9	8	8	7	9	1
WI	9	6	7	3	5	1
WY	1	1	1	7	9	7

[a] The larger the number, the greater the sensitivity to the impact category.
[b] Two-Letter U.S. Postal Codes for States.
[c] NA = Not Available.

5.2 State-normalized impact categories

State-normalized impact categories include Acid Deposition ("acid rain"), photochemical oxidant ("Smog") Creation, Water Use, Suspended Particulates (PM_{10}), Carcinogenicity, Solid Waste Disposal Land Use, Resource Extraction/Production Land Use, and Eutrophication. Since these state-normalized impact categories are relevant to fairly large areas, but are clearly not global or limited to one site, the regional data selected for the normalization factor was the maximum annual state total impact (total emissions of relevant chemicals multiplied by a regional scaling factor). Although a slightly larger or smaller area might be more appropriate for determination of normalization factors for some of the state-normalized impact categories, inventory emission data are primarily available by state, and regional scaling factors were developed to meet this limitation.

5.3 Facility-normalized impact categories

Facility-normalized impact categories were limited to the three acute toxicity categories: Human Inhalation Toxicity, Terrestrial (wildlife) Toxicity, and Aquatic (fish) Toxicity. The area within which a single organism is potentially impacted for each of these toxicity categories is typically very small. Thus, the worst case, total potential impact used for determining the normalization factor was considered to be the maximum annual emission of relevant chemicals emitted from a single facility in the United States into the environmental medium of concern. This value was used for the BDO LCIA without modification, but was revised slightly in the GBU-24 study, which was completed later. For the GBU-24 study, the normalization factor was multiplied by a factor of 1.5 to compensate for facility clustering, where facilities emitting the same chemical are co-located. Thus, the normalization factor for inhalation toxicity involved the maximum air emissions per relevant chemical from a single facility anywhere in the U.S. To test the facility clustering concept, maximum annual air emissions for a particular chemical from a single facility in the U.S. were compared with the total annual air emissions for the same chemical from the entire county where the maximum facility is located. This comparison indicated that co-located facilities seldom exceed more than 1.5 times the U.S. maximum annual air emissions for a single facility. In fact, the total annual air emissions for a single chemical from counties known to have substantial industry present was typically lower for the entire county than for the single facility emitting the maximum annual air emissions for the same chemical in the U.S. Examples of counties evaluated that are known to have substantial industry present included: Harris County, Texas, which includes Houston; Lake County, Indiana, which includes Hammond and Gary; and East Baton Rouge Parish, Louisiana, which includes most of Baton Rouge.

The normalization factor for a particular impact category was determined only for the chemicals relevant to one or more of the impact categories identified in the specific LCI under consideration. The exceptions to this rule are for the two global impact categories based on emissions (Ozone Depletion and Global Warming). For these two categories the normalization factor was based on available data for all chemicals known to contribute to these impacts, whether these chemicals were part of the LCI or not. For global Resource Depletion and all regional or local impact categories, the normalization factor was based only on the natural resources or chemicals reported in the LCI for which equivalency factors have been determined. For these later impact categories, the total impact relevant for normalization depends on which chemicals are being considered. For example, the total worldwide use of bauxite does not have any direct relationship on the total worldwide use of silica. Similarly, the total inhalation toxicity of chemical A in Columbus, Ohio does not have any direct relationship to the total inhalation toxicity of chemical B in Los Angeles, California. A sensitivity analysis was performed to verify the reasonableness of using only the list of chemicals included in the LCI as part of the normalization factor for local impact categories. This method for determining the state-based and facility-based normalization factors from chemicals in the LCI, as well as the difference in calculating the three toxicity impact categories to account for facility clustering, accounts for the differences between normalization factors for the same impact category in the two test cases (→ *Table 3, p. 206*).

6 Normalized Impact Scores for Case Studies

Normalized impact scores can be used to make comparisons within the same impact category between alternatives or between different impact categories within a particular study. It should be recognized that these types of comparisons are made prior to the valuation weighting process. Therefore, comparison of normalized impact scores between alternatives for the same impact category are the most meaningful, since no assumptions need to be made about the relative differences in magnitude between different impact categories. This was only possible for the BDO LCIA test case, where the petroleum-based and corn-based production methods were compared (EPA, 1997a). For the GBU-24 bomb LCIA, only the baseline case was evaluated, so comparisons were made between impact categories prior to valuation weighting (EPA, 1997b).

The normalized impact scores for the conventional and alternative BDO production processes (EPA, 1997a) were compared for 13 impact categories indicated in **Table 1**. The normalized impact scores were judged to be essentially the same between the two processes, when the alternative process was within 20% of the conventional process for the same impact category. Given the potential for error in the available LCI data (both secondary and modeled estimates were used), the impact equivalency factors used (especially the partial equivalencies), and data used for normalization factors, a judgement call was made that 20% variability in the resulting normalized impact scores should not be considered significant.

Table 3: Calculation of impact category normalization values based on most relevant geographic maximum extent of impact

Impact Category	Geographic Maximum Extent of Impact (Measurement Quantity)	Normalization Value (Measurement Quantity X EF)[a]	
		BDO LCIA (EPA, 1997a)	GBU-24 LCIA (EPA, 1997b)
Ozone Depletion	(total annual air emissions per chemical in world)	2.16×10^{9} kg/yr[b]	21.6×10^{9} kg/yr[b]
Global Warming	(total annual air emissions per chemical in world)	4.67×10^{13} kg/yr[c]	4.67×10^{13} kg/yr[c]
Energy Resource Depletion	(total annual production per energy resource type in world)	4.44×10^{12} MJ/yr[d]	ND
Total Resource Depletion	(total annual production per resource type in world)	ND	1.03×10^{11} kg/yr[p]
Acid Rain	(max. annual state total air emission per chemical in U.S.)	2.39×10^{10} kg/yr[e]	2.38×10^{10} kg/yr[e]
Smog Creation	(max. annual state total air emission per chemical in U.S.)	1.17×10^{9} kg/yr[f]	1.17×10^{9} kg/yr[f]
Water Use	(max. daily state total fresh water use in U.S.)	1.27×10^{7} MLD[g]	NA
Suspended Particulates (PM-10)	(max. annual state total air emissions in U.S.)	8.85×10^{8} kg/yr[h]	8.85×10^{8} kg/yr[h]
Human Inhalation Toxicity	(max. annual facility air emissions per chemical in U.S.)	6.53×10^{9} kg/yr[i]	6.89×10^{9} kg/yr[i]
Carcinogenicity	(max. annual state total emissions per chemical in U.S.)	1.10×10^{10} kg/yr[j]	2.06×10^{6} kg/yr[j]
Solid Waste Disposal Land Use	(max. annual state total industrial solid waste volume in U.S.)	6.83×10^{7} m^3/yr[k]	6.83×10^{7} m^3/yr[k]
Resource Extr./Prod. Land Use	(max. annual state total land use "intensity" per resource in U.S.)	2.93×10^{10} ha-yr[l]	NA
Terrestrial (Wildlife) Toxicity	(max. annual facility solid waste emissions per chemical in U.S.)	2.03×10^{8} kg/yr[m]	9.80×10^{6} kg/yr[m]
Aquatic (Fish) Toxicity	(max. annual facility water emissions per chemical in U.S.)	1.20×10^{8} kg/yr[n]	1.76×10^{8} kg/yr[n]
Eutrophication	(max. annual state total emissions per chemical in U.S.)	9.48×10^{8} kg/yr[o]	4.04×10^{8} kg/yr[o]

[a] EF = Equivalency Factor; ND = Not Determined; NA Not Available

[b] Based on sum of 1985 (OTA, 1991) or 1990 (IPCC, 1992), global, annual, man-made emissions per chemical times ODP equivalency factors (HEIJUNGS, 1992)

[c] Based on sum of 1988 (WUEBBLES and EDMONDS, 1991) or 1990 (IPCC, 1992), global, annual, man-made emissions per chemical times GWP equivalency factors (HEIJUNGS, 1992) over a 100-yr time horizon

[d] Based on 1994 data from DOE/EIA (1995), Annual Energy Review, DOE/EIA-0384(94), for world total annual production per energy resource type times the Resource Depletion equivalency factors (global production divided by global reserves)

[e] The maximum state acid deposition air emission impact per chemical after multiplication times the state regional scaling factor and acid deposition equivalency factor, based on data for NO_2 and SO_2 from AIRS EXEC for the years 1988-1995 and data on ammonia and HCl from TRI for 1993

[f] The maximum state VOC air emission impact is for the state of Texas after multiplication times the state regional scaling factor (8 for Texas) based on data from AIRS EXEC for the years 1988-1995

[g] The maximum state fresh water use impact is for California, based on a use rate of 1.27×10^7 million liters per day (MLD) for 1990 (SOLLEY et al., 1993) times the regional scaling factor of 9 for the state of California

[h] The maximum state PM-10 air emission impact is for the state of Indiana after multiplication times the state regional scaling factor for large sources >90.7 metric tons per year (MTPY) (9 for Indiana) based on data from AIRS EXEC for the years 1988-1995

[i] Based on sum of 1993, max. annual air emissions per chemical by facility in U.S. times Human Inhalation Toxicity equivalency factors

[j] Based on sum of 1993, max. state total annual emissions per chemical times Carcinogenicity equivalency factors

[k] Based on maximum state total industrial solid waste volume for four states contacted which had available data (Ohio, New York, Texas, and Indiana); 1994 data reported for the state with the maximum volume (Ohio) assumes that the waste is compacted to 2.53 m^3/MT

[l] Based on the maximum annual state total land use "intensity" per resource in U.S., where "intensity" is the average annual acres of land that are unavailable for other uses due to production or extraction of a particular resource. The calculation for wells or mines are based on the average production per year over the total useful lifetime of the extraction facility (e.g., oil and natural gas wells are assumed to be 0.2-ha in size and to last 30 years). The maximum natural gas producing state is Texas and the maximum corn producing state is Iowa

[m] Based on sum of 1993, max. annual solid waste emissions per chemical by facility in U.S. times Terrestrial Toxicity equivalency factors

[n] Based on sum of 1993, max. annual water emissions per chemical by facility in U.S. times Aquatic Toxicity equivalency factors

[o] Based on sum of 1993, max. state annual air and water emissions per chemical after multiplication times the state regional scaling factor and Eutrophication equivalency factor, based on data for NO_2 from AIRS EXEC for the years 1988-1995, data on ammonia from TRI for 1993, and data on fertilizer addition (USDA, 1995) and maximum runoff percent (The Fertilizer Institute, 1982)

[p] Based on 1994 data from DOE/EIA (1995), Annual Energy Review, DOE/EIA-0384(94), for world total annual production per energy resource type and 1995 data on mineral resources from the Minerals Commodity Summaries available on the World Wide Web times the Resource Depletion equivalency factors (global production divided by global reserves)

Since only the baseline GBU-24 production process was evaluated in the LCIA (EPA, 1997b), evaluation of the normalized impact scores can only be used to make comparisons between impact categories if each of the 11 impact categories evaluated in this case study are assumed to have the same relative importance. Thus, only impact categories with normalized impact scores which were greater than one order of magnitude more than any of the other impact categories were considered to have a higher potential for environmental impact. When the normalized impact scores were summed and each impact category score was calculated to be a percentage of that sum, the Carcinogenicity and Terrestrial Toxicity impact category scores made up 46% and 41%, respectively, of the sum for all impact categories combined. Thus, assuming that valuation would not substantially change these percentages, reduction in the chemicals contributing to these two impact categories should be considered the highest priority for making life-cycle improvements in GBU-24 production. Each of these two highest normalized impact potential scores was more than 20 times greater than the next highest impact category.

7 Conclusions and Limitations

As a result of the method development and application of regional scaling and normalization approaches for improving the accuracy of LCIA discussed above, the following conclusions can be made:

- Regional scaling methods based on water use and availability, sensitive receptor distribution, emission sources, and/or emission deposition quantities were developed to improve the accuracy for the following five regional environmental impact categories: Suspended Particulates (PM_{10}), Water Use, Acid Deposition, Smog Creation, and Eutrophication.
- The geographically relevant normalization method was described and tested. Data for state-normalized and facility-normalized impact categories resulting from chemical emissions were available through the electronic databases AIRS EXEC and TRI.
- Use of 1.5 times the maximum U.S. annual facility emission as a normalization value for any of the three toxicity impact categories appears to consider the worst case where facilities emitting the same chemical into the same medium are clustered.
- This system of regional scaling and normalization worked well for two LCIA case studies in the U.S. involving up to 14 impact categories. Appropriate regional and local data may not be available for some other countries.

Although the regional scaling and normalization approach worked well for the two case studies, the following limitations should be considered before using on other LCIAs:

- The regional scaling approach uses an average sensitivity value (regional scaling factor) for an entire state. Thus, the regional scaling factors are only appropriate for LCAs with numerous emission sources and may not necessarily reflect the sensitivity at a specific site, which would be important for an LCA with only a few emission sources.
- Three of the five regional scaling factors involving air emissions (Suspended (PM_{10}) Particulates, Acid Deposition, and Smog Creation) were partially based on maps of emission sources (as surrogates for background concentration information) and partially based on maps of non-attainment areas (with air concentrations above the threshold of concern). For the emission source maps, it was assumed that the majority of the air emissions had the potential to cause these effects in the same state where they were released, although it is recognized that air emissions from tall stacks can be carried beyond state boundaries. A modeling-based source distribution approach has already been developed for acid deposition and could be adapted for the other air emission impact categories.
- Normalization factors for eight regional and three local impact categories were based, respectively, on the maximum annual, state total impact and 1.5 times the maximum annual, facility total impact. The state and facility methods of normalization were selected, because it is believed that they represent readily available data that are reasonably close to the actual total impact for categories considered to be regional or local in spatial influence.

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